Prediction of Organic Combined Sewer Sediment Release and Transport

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Abstract: Accurate predictions of sediment loads released by sewer overflow discharges are important for being able to provide protection to vulnerable receiving waters. These predictions are sensitive to the estimated sediment characteristics and on the site conditions of in-pipe deposit formation. Their application without a detailed analysis and understanding of the initial conditions under which in-sewer deposits were formed normally results in very poor estimations. In this study, in-sewer sediment samples deposited during dry periods in a combined sewer system were collected, and their properties assessed. Parameters in a sediment transport relationship for in-pipe deposits were estimated by simulating the in-pipe deposit formation conditions in laboratory erosion tests. The measured parameters were then used to simulate sediment transport through a small combined sewer network for a number of rain events for which rainfall, hydraulic, and water quality data were available. Results showed that the model of Skipworth can provide good predictions of the sediment loads released from such in-sewer deposits. The experimentally derived calibration parameters used with Skipworth's model allowed for a realistic simulation of the in-sewer sediment behavior, and so can be used to accurately estimate the sediment load released from combined sewer systems during rainfall events. **DOI: 10.1061/(ASCE)HY.1943-7900.0001422.**

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Introduction

Existing software packages for the hydraulic modeling of sewer network systems generally show good predictive performance. However, the simulation of water quality processes in sewer system network models has been less reliable (e.g., Ashley et al. 1999; Kanso et al. 2005) and sewer flow water-quality data are generally less available (e.g., Willems 2010).

Water quality modeling in combined sewer systems predicts sediment and pollutant loads for time-varying flows. Research has shown that a significant contribution of suspended sediment originates from the release and resuspension of sediment from in-sewer deposits during the initial period of storms (Ahyerre and Chebbo 2002; Ashley et al. 2004; Gromaire-Mertz et al. 2001; Saul and Thornton 1989; Tait et al. 2003a). The rapid suspension of previously deposited in-pipe sediment has been observed in releases from combined sewer overflows during intense rainfall events. This phenomenon has been termed first foul flush (Gupta and Saul 1996). The first flush phenomenon (Obermann et al. 2009) is often observed in regions with a semiarid climate, such as in Mediterranean catchments, which are characterized by dry-weather periods (DWPs) followed by intense storm events. The high variability of the flow regimes of the rivers in these regions are also strongly dependent on the seasonal rainfall; this can result in a quite limited dilution capacity of the natural receiving waters (Prat and Munné 2000). Thus, in areas of water scarcity, first flush can have a very significant impact. In the Mediterranean region where the case study catchment is based, it is therefore important to achieve reliable predictions of sediment and pollutants loads that can reach the receiving waters through combined sewer overflows (CSOs) during intense rainfall events. An improved prediction of sediment loads could allow for action to better manage pollutants that are released and are known to generate high oxygen demand in receiving waters. Most sediment transport research has been focused on sediment movement in rivers. The findings resulted in predictive relationships, empirically calibrated and developed from observations of the movement of mainly granular sediments. The application of existing granular-based fluvial transport models, such as Ackers (1984, 1991) and May (1993), modified to simulate erosion and transport of granular and organic sediments through piped sewer systems, does not perform well (Ashley et al. 2004; McIlhatton et al. 2005; Schellart et al. 2008b; De Sutter et al. 2003). Considering the additional processes that can occur in sewer sediment deposits, the use of sediment transport relationships originally developed for fluvial environments and granular sediment can be reasonably questioned.

Biochemical transformation processes, interactions between particles, and microbiological activity can have a significant influence on the resistance to erosion of in-pipe deposits (Banasiak and Tait 2008; McIlhatton et al. 2005; Sakrabani et al. 2005; Seco et al. 2014b; Vollertsen and Hvitved-Jacobsen 2000). The available sediment transport relationships for cohesive deposits oversimplify the process occurring in sewers (Freni et al. 2008; Mannina et al. 2012; Schellart et al. 2010).

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The deposit erosion methodology developed by Skipworth et al. (1999) links the sediment erosion rate to critical shear stress levels related to different layers within the sediment deposit in pipes. The methodology is derived from laboratory observations obtained from the erosion and transport of cohesivelike synthetic sediment previously deposited in a pipe and subjected to steady flow conditions.

Results obtained by Skipworth et al. (1999) and later verified by Rushforth et al. (2003) confirm that their methodology improves prediction of the transport rate of cohesive sediment. The potential for improvements in the prediction of sediment erosion rates when using Skipworth's model can only be attained if realistic values for the calibration parameters of the deposit erosion model can be obtained. In this study, field data is used to test this type of deposit erosion to assess its utility for modeling sediment releases from sewer system overflows during intense rainfall events.

The determination of shear stress at the threshold of motion (τ_c) exerted on the sediment bed surface is crucial in the evaluation of the release of sediments from layered deposits; however, this threshold is difficult to determine in situ. Mclhatton et al. (2005) and Oms et al. (2008) reported observed values of τ_c in the range of 0.15 to 0.85 $\mathrm{N/m^2}$ for in-sewer sediment deposits in combined sewer systems in Dundee (Scotland) and Paris (France), respectively.

Highly organic sediment deposits can be observed in combined sewer systems serving highly urbanized areas in the Mediterranean region where high levels of catchment imperviousness are common. Additionally, large fluctuations in combined sewer flows are associated with semiarid climates, and this pattern of variation can have an effect on the sediment accumulation–flushing cycles found in sewer networks. The main aim of this paper is to examine the suspended sediment load evolution that can be discharged into natural watercourses from CSOs activated during intense rain events. The accurate estimation of the sediment discharge pattern will help in quantifying the impact of CSOs on receiving waters. With this aim, the study had the following objectives: to evaluate the process of mobilization from in-sewer sediment deposits, and to validate Skipworth's deposit relationship in a particular catchment under realistic rainfall conditions.

To achieve these objectives, the empirical deposit and transport parameters were estimated from laboratory observations. The performed tests allowed the analysis of the erosion behavior of highly organic sediment sampled from a real sewer network. Previous investigations on the erodibility of highly organic sediment (Seco et al. 2014a) provided key knowledge on the properties of sediment recovered from the same combined sewer system. The experimental and analytical procedures were modified on the basis of the results obtained in the earlier study. Controlled environmental temperature conditions were now established. An intermediate DWP between the formerly established 16 and 64 h was also implemented to obtain a deeper comprehension of the process that influences erosion rate evolution. The results obtained from the laboratory experiments reported in this paper allowed for the assessment of the calibration parameters involved in the deposit-erosion model proposed by Skipworth et al. (1999). The use of real sewer sediments for the determination of the transport parameters allowed for the verification of the application of the Skipworth's in-pipe deposit model at a network scale.

Methods

Study Site Location and Description

The field study site is situated in the southeast of Spain, in the city of Granollers (35 km north of Barcelona, Spain). The local rainfall pattern is irregularly distributed throughout the year and characterized by dry-weather periods often longer than a week followed by single storm events. A small urban catchment in Granollers was selected for the study, covering an area of approximately 10 ha (Fig. 1). The land use is mainly residential and commercial, with a

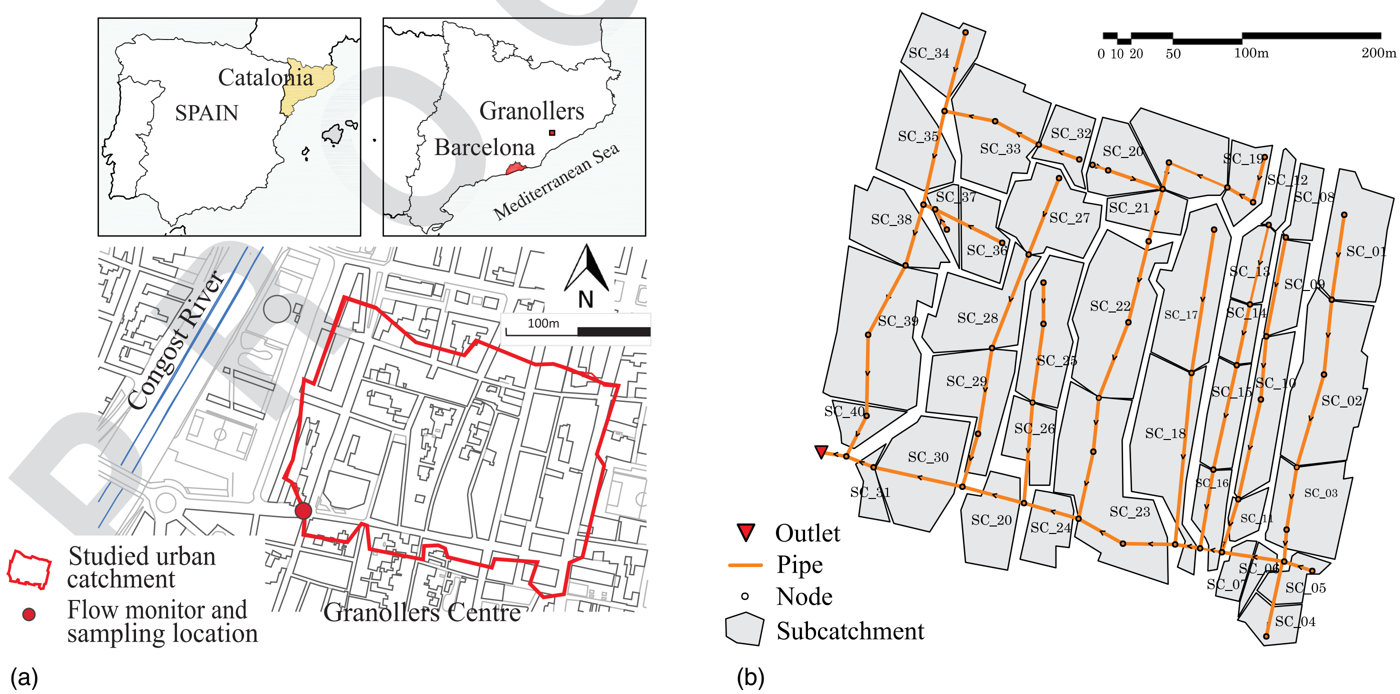


Fig. 1. (a) Location of the study urban catchment adapted from official cartographic data (map data © 2017 Institut Cartogràfic i Geològic de Catalunya); (b) layout of the combined sewer network and catchment subdivision for the hydrodynamic and quality modeling

Table 1. General Characteristics for the Catchment and Combined Sewer Network of the Study Site

Parameter	Value
Catchment	
Area	10.1 ha
Surface slopes	Between 0.5 and 2.15%
% impermeability	Between 77 and 93%
Combined Sewer Network	
Average wastewater flow at outlet	24 m^3/h
Total length of pipes	2.2 km
Pipe diameters	300–1,000 mm

high population density of 150 inhabitants/ha. The area has a significant presence of commercial food activity. The catchment surface displays a high degree of imperviousness that reaches almost 100% in some zones, with an average imperviousness of 84% over the whole catchment. Given the highly impervious conditions of the catchment and the limited existence of soil areas, inorganic sediments are a minor contribution during storm runoff (Gómez-Valentín et al. 2015).

The urban area has a gravity-driven combined sewer system composed of circular concrete pipes with diameters ranging from 300 to 1,000 mm. General characteristics of the catchment and the combined sewer network are given in Table 1.

Hydrological, Hydraulic, and Water Quality Monitoring

Flow rates, water quality data, and rainfall data were collected during storm events. The purpose of the monitoring program was to obtain field data to validate the reported modeling work. The layout and the operation of the case study sewer network is similar to that of many other combined systems throughout Europe and the eastern coast of the United States. The results of the study are therefore expected to be widely applicable. The monitoring program was carried out over an 18-month period. The events of interest were selected on the basis of two threshold conditions: a rainfall depth which would produce enough runoff to increase water depths and velocities in the sewer network and also have sufficient flow to produce a measurable resuspension of sediments previously deposited inside the network, and an antecedent DWP sufficient to produce enough sediment accumulation for the detection of increasing pollutant loads at the outlet of the analyzed catchment. Precipitation depth of 5 mm and antecedent DWP of the order of several days were established as thresholds. Events that experienced major disruptions during flow recording or water quality sampling were discarded. After preprocessing, four rainfall events satisfying these conditions remained; see events 1 to 4 in Table 2. For these events, physical samples for water quality analysis were collected at the outlet of the catchment simultaneously with rainfall data and flow data. Two additional events where no satisfactory water quality data were recorded (events 5 and 6 in Table 2) were used to calibrate the network hydrodynamic model.

Flow was continuously monitored using an automatic portable flowmeter (HACH-Lange, Sigma 950 model). The instrument was provided with a bubbler water level sensor and a doppler velocity sensor, and the flow rate was then calculated. The water samples were collected during rainfall with an automatic sampler (HACH-Lange Sigma SD900 model). The sampler was equipped with a peristaltic high-speed pump taking in 1,000 mL in 2 min through a tube with a strainer at the end, followed by a cleaning cycle that took another 2 min. An increase in flow rate compared with the dry-weather flow pattern triggered the collection of water quality samples. Due to the high imperviousness of the catchment, it was expected that the runoff rapidly releases and washes off sediments from the surface and erodes them from inside the network. The highest sampling frequency was therefore set at 5 min for the first 15 min of a rainfall event, and then less frequently for a total of 2 h. Following the trigger at $t = 0$, samples were taken at 0, 5, 10, 15, 30, 45, 60, 90, and 120 min. The established sampling frequency was intended to focus on the beginning of a storm event in order to analyze the occurrence of a first flush pollutant phenomenon.

Deposited Sediment Characteristics and Behavior

Sediment Deposit Sampling and Analysis

A batch of 3 kg of in-sewer sediment was manually collected directly from the invert of a 600-mm pipe with 0.002 m/m slope upstream of a diameter reduction (from 600 m to 400 mm). According to the local operators, sediment deposit formations were typically observed in this section after prolonged dry periods. The collection was conducted during dry-weather flows when the water depth was less than 5 cm. The deposited sediments were collected manually, immediately refrigerated at 4°C, and then transported within 48 h to Sheffield in the United Kingdom, where the analysis and erosion tests were performed. Upon arrival in Sheffield, the sediment temperature was found to be 4.7°C, after which the sediments were immediately stored in a refrigerator at 4°C. Despite the destruction in the layer structure of the deposit during collection, no alterations were believed to have taken place in the physical characteristics of the sediments, whereas biological activity and microbiological decomposition of the sediment samples were inhibited by the low temperatures during the storage and transport procedures. Thus, for physical characterization, the collected sediment was considered representative of the deposit formed in the invert of the original sewer pipe during dry-weather periods.

Analysis and sediment preservation follow the procedure set out in *Standard Methods for the Examination of Water and Wastewater* (APHA et al. 2005). A summary of the sediment characteristics is shown in Table 3.

Table 2. Rainfall Events Registered in the Study Site and Used for the Sediment Transport Modeling Validation

Registered data	ID	Date	Total rainfall depth (mm)	Maximum intensity (mm/h)	Duration (min)	Antecedent dry-weather period length (days)
Rainfall, flow and quality	1	September 17, 2010	19.0	36.2	130	28
	2	May 31, 2011	26.2	33.5	315	16
	3	October 24, 2011	6.4	37.0	80	39
	4	July 13, 2011	11.1	18.2	235	6
Rainfall and flow	5	October 9, 2010	33.5	36.6	605	21
	6	March 12, 2011	71.6	18.2	1,130	22

Table 3. Characteristics of Sediments Used by Skipworth et al. (1999), Rushforth (2001), Seco et al. (2014a), and in This Work

Sediment type	Data source	Characteristic particle size d_{50} (mm)	Sediment density (kg/m^3)	Organic content (%)
Sewer sediment from urban	Seco et al. (2014a)	0.31 ($\pm$0.16)	1310 ($\pm$146)	74 (VS/TSS)
catchment in Granollers, Spain	Batch used in this work		1313 ($\pm$95)	95 (VS/TSS) $\pm$2
Crushed olivestone	Skipworth et al. (1999) and Rushforth (2001)	0.047	1,445	100

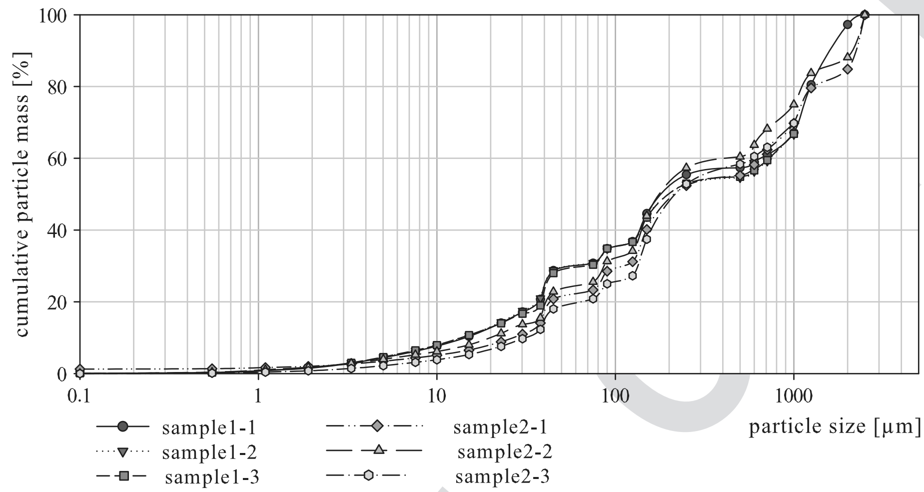


Fig. 2. Particle size distribution in raw sewage deposited sediments at Granollers, Spain. PSD performed with standard sieve (>1 mm subsample) and laser diffraction analysis (<1 mm subfraction)

The sediments were characterized for organic content, which is defined as the proportion between the volatile solids (VS) and the total dry mass of sediments (TS) (section 2540E, *Standard Method*). An average of 95% $\pm$2 of VS:TS rate was obtained. The density of the deposit was assessed using the displacement principle method. The presence of fat, oil, and greases was established through visual observation of the sediment. The characteristic particle diameter d_{50} was obtained following the British Standards (BS 1796-1:1989. test sieving) for the gross part (>1 mm), whereas the fine part (<1 mm) was performed by laser diffraction method (ISO 13320:2009 Particle size analysis. Laser diffraction methods) using a Mastersizer 2000, Malvern instrument Ltd. Fig. 2 shows the particle size distribution curve of the collected sediment samples.

Laboratory Erosion Test Procedure

The laboratory tests were carried out with a sample of sewer sediment deposit placed in a device called an erosionmeter (developed by Liem et al. 1997). The erosionmeter consists of a vertical perspex tube provided with a centrally located propeller and vertical vanes to reduce lateral circulation, and a container for the sediment deposit. By applying an angular velocity to the water column, a reasonably uniform shear stress is exerted over the sediment surface. Six vertically spaced outlets are used to sample the sediment eroded from the bed that remained suspended in the water column. The samples were analyzed later for TSS following the *Standard Methods for the Examination of Water and Wastewater* (2005). A detailed description of the equipment and calibration process is given in Seco et al. (2014a).

The preparation of the samples followed a defined procedure with the intention of establishing repeatable conditions and to simulate the dry-weather flow conditions found in the case study sewer. The whole batch of collected disturbed sediment deposit was thoroughly mixed and separated into individual samples. The container with the individual sediment sample was then carefully filled with water and left for 72 h at 4°C in a phase of quiescent physical consolidation where the biological reactions were retarded by the low temperature. After the preconsolidation phase, the sample was placed in the bottom of the erosionmeter and allowed to assimilate to 20°C. Aerobic conditions were set by supplying air to the supernatant water. An oxygenated environment in a gravity sewer network is likely to be produced under conditions of varying flows (Hvitved-Jacobsen et al. 2013). A low bed-shear stress (0.15 N/m^2), similar to that found during dry-weather flows in the system, was applied over the bed by slowly rotating the propeller. By applying a low bed-shear stress, it was intended to simulate the dynamic consolidation conditions at which sediment deposits were subjected in sewers during periods of sediment deposition between rain events (DWP). Additionally, the low velocity of the propeller ensures a continuous mixing and creates a uniform environment regarding water temperature and dissolved oxygen (DO) levels. The results from this study focus, therefore, on the erosion and transport of sediments subjected to aerobic conditions at 20°C during the depositional DWP prior to a storm, and the tests were carried out in a temperature-controlled room. Four different DWP durations between 16 and 64 h were considered to simulate the consolidation process thought to be present in the actual sewer system. The DWP durations were in the order of magnitude of several days for two reasons: first, although there are longer DWPs in the catchment, the average DWP throughout the 18-month field monitoring period was 3 days; second, as described in Seco et al. (2014b), the sediments were quite biologically active and it was assumed that during DWP the upper sediment layers are continuously being biodegraded as well as replenished with fresh sediments originating from the dry-weather flow. The critical threshold of motion at the solid-fluid interface of the resulting deposit was then assessed by stepwise increase of the propeller speed. The erosion phase of the tests was then performed by increasing the applied shear stress in a stepwise fashion. Samples were collected from the water column at steady erosion state conditions (Parchure and Mehta 1985) at each step of applied bed-shear stress, which lasts 45 min (Schellart et al. 2005; Tait et al. 2003b). The eroded material and resultant erosion rate was calculated from the measured suspended sediment (SS) concentration of the collected samples. These data are reported in this paper and were used in the calibration of the erosion model described subsequently.

Modeling Sediment Transport in a Field Study Catchment

Hydrodynamic Modeling

The *SWMM5* (Storm Water Management Model) software package was selected for the rainfall-runoff and hydrodynamic modeling through the combined sewer system in the study case. The hydrological model (Fig. 1) is defined based on a subcatchment delineation established from topographic data of the catchment drainage areas and of the combined sewer network, complemented by in situ observations to complete information about impervious-pervious surfaces and their drainage characteristics. The hydrodynamic network model is directly related to the sewer network system information provided by the local sewerage company; it comprises 57 pipes and manholes and 42 subcatchments in a 10-ha area. Flow measurements were performed at the outlet of the studied catchment using the equipment and procedures described previously.

A calibration and validation process of the hydrodynamic model was performed by comparing simulated with measured flow rates during several rainfall events. Model calibration was carried out using rainfall events 5 and 6 (Table 2). Subsequently, the model was validated by applying independent data sets corresponding to events 2 and 3. The relative errors of total runoff volume range from 1 to 10% for the analyzed events, which are indicated in Table 4. The relative error of peak flow is between 2 and 10%, and the difference in the elapsed time to reach the peak flow range from 2 to 8 min. The goodness of fit obtained can be observed in Fig. 3 and Table 4.

Sediment Erosion Model

The methodology proposed by Skipworth et al. (1999) is based on the concept of a bed structure with different layers, in which each layer displays a different resistance to erosion.

The simulation method proposed by Skipworth et al. (1999) is based on an excess shear stress relationship to predict the sediment erosion rate for estuarine deposits called Ariathurai-Partheniades equation [Eq. (1); Ariathurai (1974), as referenced by McAnally and Mehta (2000)]

$$E = M \cdot \left(\frac{\tau_b - \tau_c}{\tau_c} \right) \qquad (1)$$

where E = erosion rate in kilogram per square meter per second for the applied bed-shear stress, τ_b (N/m^2), and τ_c (N/m^2) is the critical shear stress; and M is a transport parameter used as a calibration

Table 4. Relative Errors Used as Goodness of Fit Measured Flow Rate with Simulated Flows during Rain Events

	Calibration events		Validation events	
Errors	Rain event 5 (October 9, 2010)	Rain event 6 (March 12, 2011)	Rain event 2 (May 31, 2011)	Rain event 3 (October 24, 2011)
Relative error of total runoff volume (%)	10	1	6	5
Relative error of peak flow (%)	10	2	7	8
Time to first peak error (min)	2	2	8	4

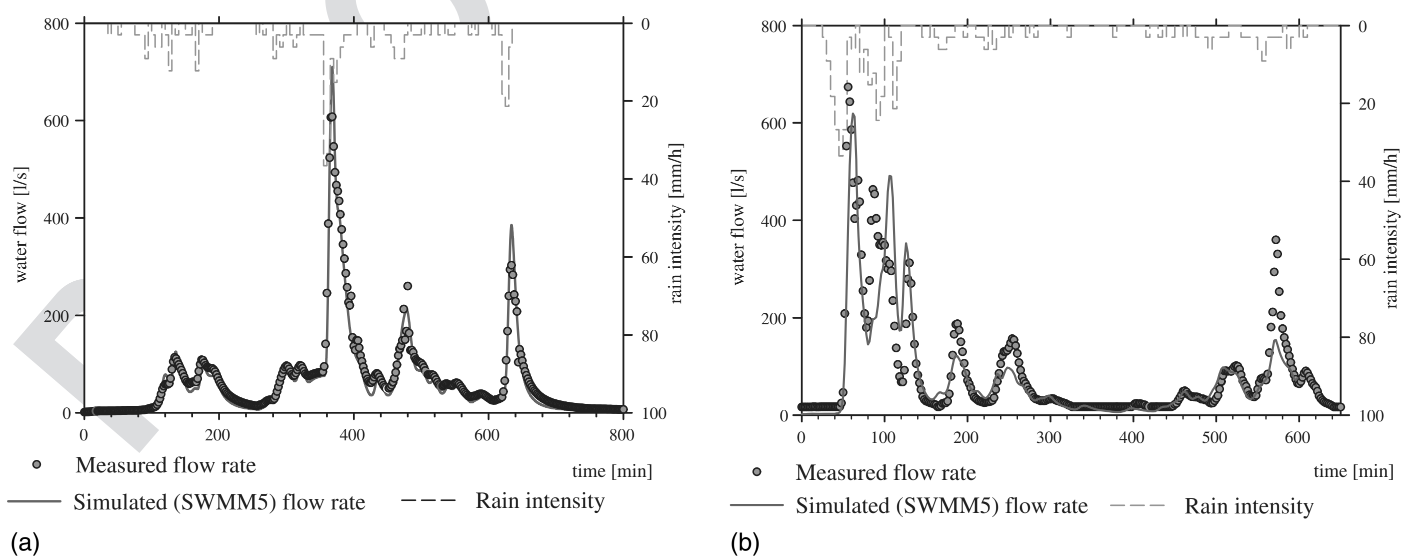


Fig. 3. Comparison between measured and calibrated hydrograph for rain events taken as examples: (a) calibration with the Rain Event 5 (simulated peak delayed 2 min); (b) validation with the Rain Event 2 (simulated peak delayed 8 min)

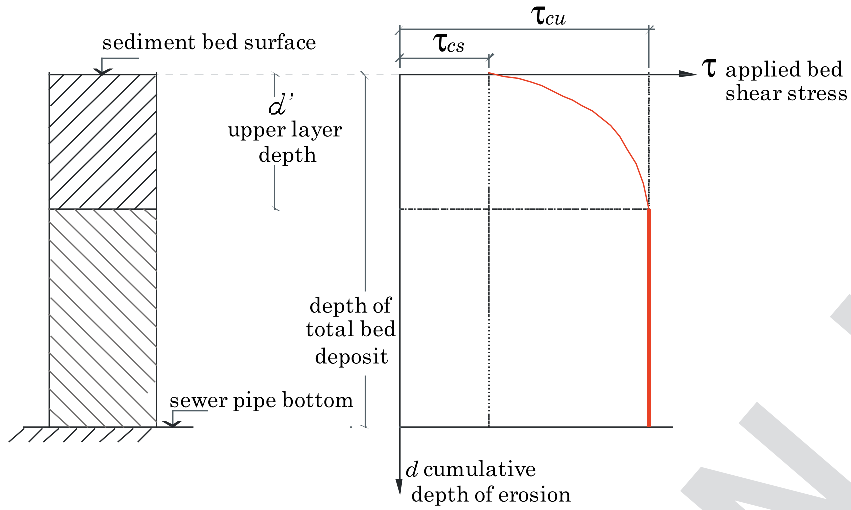


Fig. 4. Variation of the erosional resistance of the sediment deposit in a depth profile (adapted from Skipworth et al. 1999)

factor that has the same units as E and is equal to the erosion rate when $\tau_b = 2 \cdot \tau_c$.

By examining the erosion rate over time, Skipworth concluded that in-pipe deposits showed a weaker upper layer transitioning to a stronger underlying layer. It was later observed, also verified by Schellart et al. (2005) and Seco et al. (2014a), that the organic content, oxygen availability, and length of the consolidation period have an influence on the subsequent erosion resistance of the deposited layers. Fig. 4 shows the variation of the erosional resistance with depth for cohesivelike sediment deposits. At the upper layer, the erosional strength increases in depth from a surface erosional strength (τ_{cs}) until a value of deposit strength (τ_{cu}). Once the thickness of the upper layer (d') is exceeded and the lower layer is reached, the deposit has an almost uniform resistance to erosion.

Skipworth et al. (1999) proposed a power law, shown in Eq. (2), that represents the depth variation of the shear stress necessary to erode the upper weak layer.

$$\tau_c = \left[\left(\frac{\mathrm{d}}{\mathrm{d}'}\right)^{\frac{1}{b}} . (\tau_{cu} - \tau_{cs})\right] + \tau_{cs} \quad \text{for } 0 \leq d \leq d'$$
$$\tau_c = \tau_{cu} \quad \text{for } d > d' \tag{2}$$

where d = cumulative depth of erosion; d' represents the thickness of the upper layer (Fig. 4); and b is a calibration parameter that describes the rate of change in bed strength with depth. The factor M is also a model calibration parameter. Owing to the high dependency on the sediment bed properties, the values of M, b, d', τ_{cs}, and τ_{cu} must be empirically determined to obtain a realistic prediction of sediment erosion and transport.

Coupling of a Sediment Transport Model and *SWMM5*

In order to analyze the performance of this model for predicting sediment release in a combined sewer network under time-varying hydraulic conditions, the erosion relationship of Skipworth was coded using *MATLAB* and then coupled with a sediment transport network model also coded in *MATLAB*. This code was based on the concept of a model previously used by Schellart et al. (2008a), which simulates the transport of sediment eroded from in-pipe deposits, based on hydraulic parameters simulated by an uncoupled hydrodynamic sewer network model, and assuming conservation of sediment mass between sediment advection, released sediment, and the sediment stored in the in-pipe deposits. Predictions from the calibrated *SWMM5* hydraulic model were used as inputs for the sediment erosion and transport model coded in *MATLAB*. The linked modeling structure is shown in Fig. 5.

Performance Evaluation Criteria

The goodness of fit between observed and simulated SS concentration values was evaluated by using the following criteria: the sum of squared errors (SSE) [Eq. (3)]; the percent peak error (PE) [Eq. (4)]; and the Nash-Sutcliffe efficiency (NSE) [Eq. (5)] where $C_{SS,m,i}$, $C_{SS,s,i}$ are the SS concentration measure and simulated at time i, respectively, and $C_{SS,peak}$ is the concentration peak, defined as the maximum SS concentration value of the event.

Nash-Sutcliffe efficiency values range between 1 for a perfect fit and -∞

$$\mathrm{SSE} = \sum_{i=1}^{n} (C_{SS,m,i} - C_{SS,s,i})^2 \tag{3}$$

$$\mathrm{PE} = \frac{(C_{SS,m,peak} - C_{SS,s,peak})}{C_{SS,m,peak}} \cdot 100 \tag{4}$$

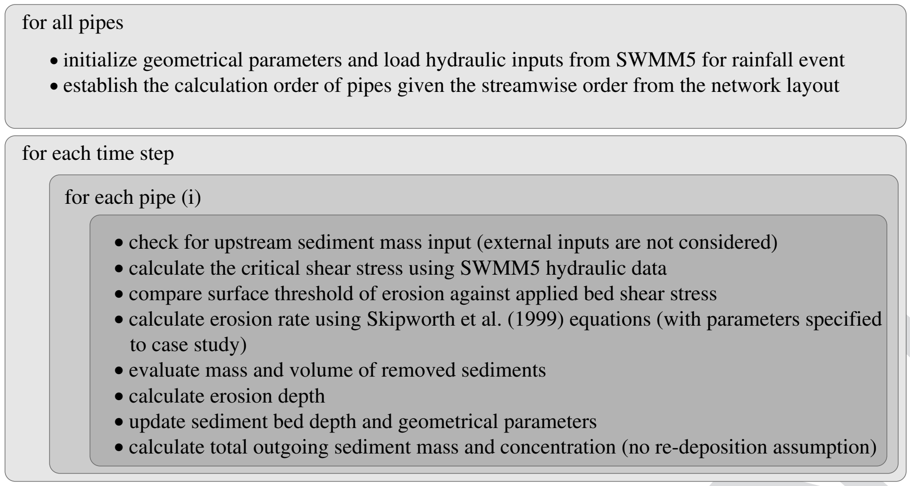
$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (C_{ss,m,i} - C_{ss,s,i})^2}{\sum_{i=1}^{n} (C_{ss,m,i} - \overline{C_{ss,m,i}})^2} = 1 - \frac{\mathrm{SSE}}{\sum_{i=1}^{n} (C_{ss,m,i} - \overline{C_{ss,m,i}})^2} \tag{5}$$

Results and Discussion

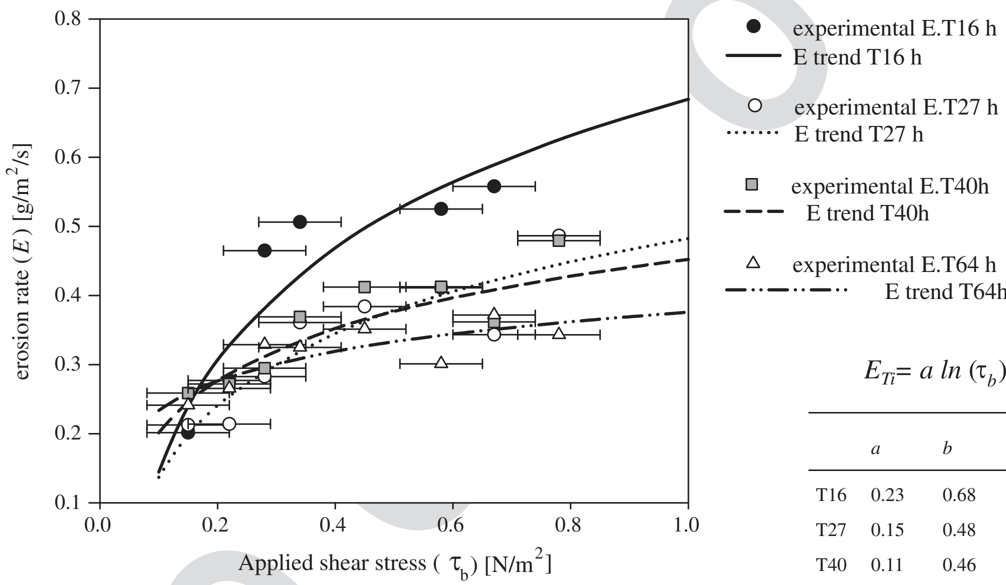
Assessment and Optimization of Transport Parameters Based on Laboratory Results

The values of the calibration parameters of the equation proposed by Skipworth [Eqs. (1) and (2)] can be derived from analysis of the data obtained from laboratory erosion tests.

The determination of the erosional strength with depth is derived from each time step application of increased shear stress linked with the stable SS concentration measured ($C_{SS,m}$) at the end of each time step. The relationship between applied shear stress and erosion rate is shown in Fig. 6, for tests carried out under aerobic conditions and for different durations of antecedent dry-weather



F5:1 **Fig. 5.** Scheme of the simplified network sediment transport module coded in *MATLAB*



$E_{Ti} = a \ln(\tau_b) + b$

	a	b	R^2
T16	0.23	0.68	0.832
T27	0.15	0.48	0.811
T40	0.11	0.46	0.768
T64	0.06	0.38	0.644

F6:1 **Fig. 6.** Erosion rate against applied shear stress; measured data, error in measurement, and regression function found

period. The errors in the determination of the applied shear stress (± 0.07 N/m^2) derived from the erosionmeter calibration process were also represented [see Seco et al. (2014a) for more detail]. Through a regression analysis, a series of best-fit trend functions were obtained (Fig. 6).

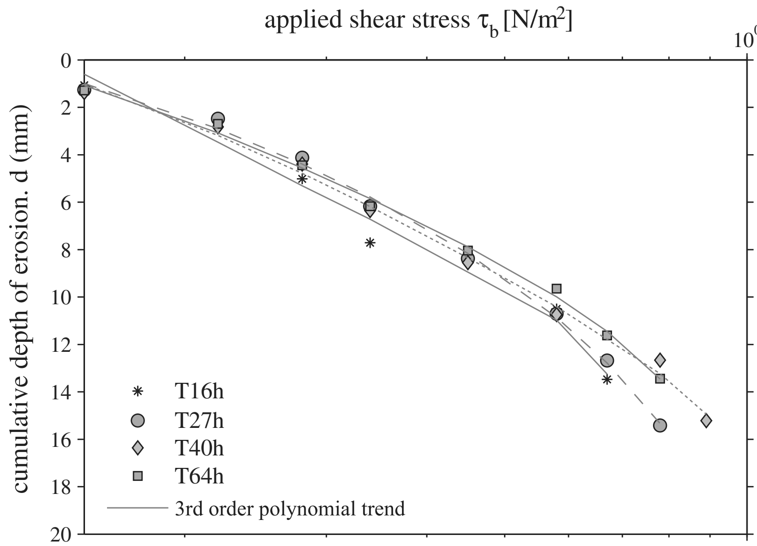
Assessment of Parameters τ_{cs}, τ_{cu}, d'', and d'

At the end of each time step during the erosion test, the mass of sediment obtained from the SS sample concentration can be translated to a sediment erosion depth (d_e), and so it is possible to link the deposit properties to the applied shear stress (τ_b). The bulk density of the bed formed by collected sewer organic-cohesive sediment is 1,310 kg/m^3 (± 146 kg/m^3). Sediment bed density was assumed to remain constant during the test because the duration of the erosion test is relatively short compared with any consolidation processes that can produce significant changes in the density of the deposit structure due to excess pore water effects.

The applied shear stress against the depth of erosion is shown in Fig. 7.

During the antecedent DWP simulated in the tests, the erosionmeter was set to exert $\tau_{DW} = 0.15$ N/m^2 on the sediment bed. This τ_{DW} value was estimated by examination of the bed-shear stress value at the outlet pipe predicted during DWF in the case study network.

It was noticed that during all DWP tested, a near-constant and thin surficial layer was eroded at the end of the consolidation period. The depth of this eroded layer can be assessed from the sample of the sediment concentration at the end of DWP [Eq. (6)], which allows establishment of the value of a parameter d'' as the observed value 1.25 mm (standard deviation SD = 0.13 mm). There were no significant changes observed in the depth of the eroded layer with different DWP durations. Hence, it is assumed that the value of the critical shear stress at the surface layer τ_{cs} can be considered equal to the applied shear stress during the



$$d_{Ti} = a\,\tau_b^3 - b\,\tau_b^2 + c\,\tau_b - d$$

	a	*b*	*c*	*d*	R^2
T16	108.76	150.12	85.21	9.17	0.987
T27	19.46	30.30	36.39	3.85	0.997
T40	22.86	46.80	45.82	4.87	0.994
T64	29.38	49.75	43.94	4.49	0.996

Fig. 7. Sediment bed depth strength against applied shear stress; measured data from erosion tests and trend

antecedent DWP (0.15 $\mathrm{N/m^2}$). This means that the τ_{cs} and d'' can be considered independent of the length of the DWP when consolidation of the sediment deposit takes place

$$d_e = \left(C_{\mathrm{SS}} \cdot \frac{V_s}{A_s} \right) \cdot \frac{1}{\rho_s} \tag{6}$$

Following the profile of sediment resistance against erosion shown in Fig. 4, the value of τ_{cu} would be obtained when the resistance strength becomes uniform with depth. The experimental tests, however, did not achieve a completely uniform resistance against erosion. Therefore, the thickness of the upper layer of sediments (d') is estimated by assuming that a gradient of 0.03 ($\Delta\tau_b/\Delta d$) practically marks the transition between the upper layer (d') and the lower more uniform layer. Fig. 8(a) shows the values of d' and τ_{cu} estimated from the erosion tests performed after different consolidation periods; a dot marks the estimated transition point below which the τ_{cu} is assumed to be sensibly constant. In Fig. 8(a), the errors in the assessment of the sediment depth of erosion (± 6 mm) and the accuracy of the applied shear stress (± 0.07 $\mathrm{N/m^2}$ after Seco et al. 2014a) are indicated by shaded error bands. From this plot it can be observed that after 24 h of consolidation, the increase in the resistance against erosion of the sediment bed is not significant.

Determination of the Values Adopted by the Model Parameters *b* and *M*

In order to apply Eqs. (1) and (2), the values of the parameters M and b need to be determined. An optimization for calibration parameters b and M is therefore performed by comparing the calculated erosion rate E_c against measured erosion rate E_m, given the applied shear stress τ_b. This optimization was carried out by varying both parameters at the same time, in order to obtain a minimum value for the root-mean square error (RMSE) [Eq. (7)]

$$\mathrm{RMSE} = \sqrt{(E_c - E_m)^2} \tag{7}$$

The ranges in which the values of the parameters b and M were varied during the optimization were initially assumed to be those determined by Skipworth and Rushforth and presented in Table 5. However, this did not lead to a minimum, hence the range of variation for the b parameter was increased to 0.025 and 1 (with increments of 0.025), and for the M parameter varying from 0.05 and 2 (with increments of 0.05).

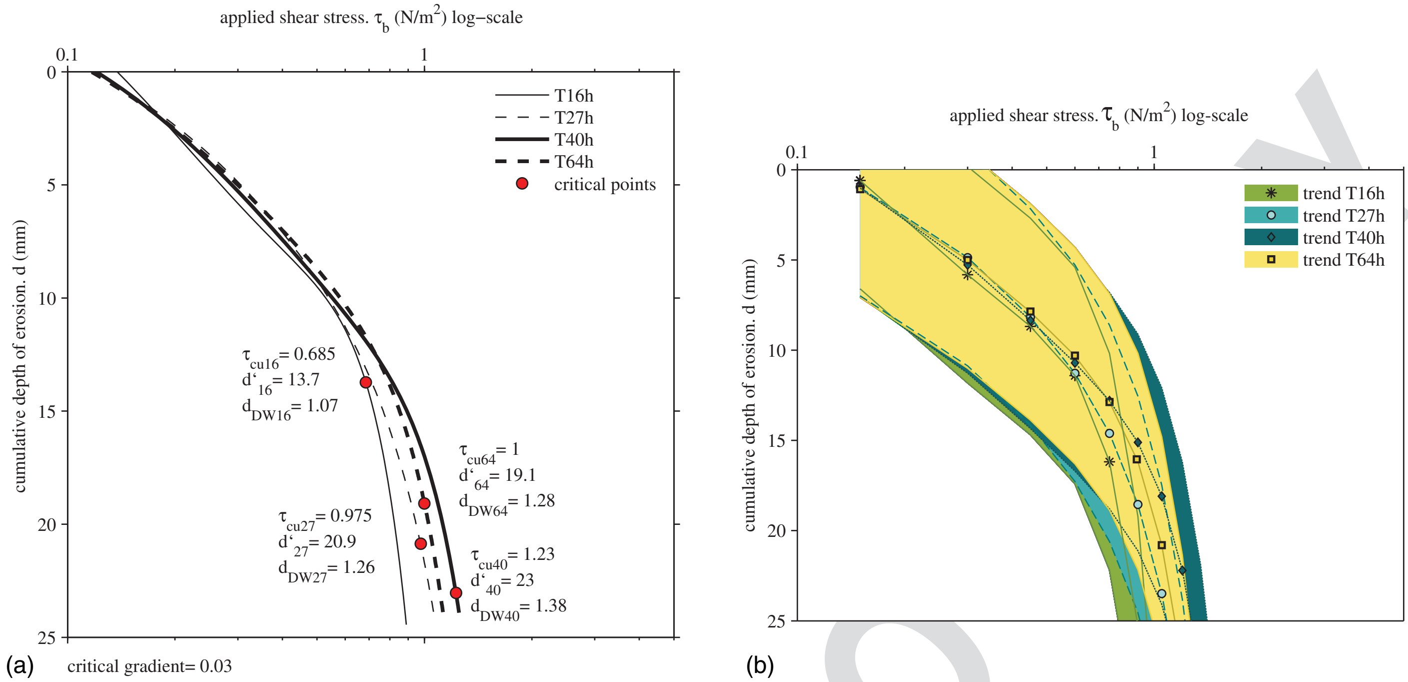
The optimization results produced a narrow range of values for b [Fig. 9(a)] where the mean value obtained is $b = 0.125$ (SD $= 0.071$). Regarding the value of the parameter M, the variation is wider [Fig. 9(b)]. However, a relationship between the value adopted by the M parameter and the applied shear stress for each test could be observed, and this trend changes with the length of the DWP analyzed. Thus, it can be suggested that a weak relation exists between the duration of the consolidation period and the parameter M (coefficient of proportionality between 0.51 and 0.74). The optimized values for b and new ranges found for M and the other parameters involved in the calculation or erosion rate are included in Table 5.

Fig. 8 indicates that after 24 h of consolidation, the resistance against erosion throughout the depth of the deposit stabilized. Based on that finding, the values of the sediment transport parameters b and M that were used for the network sediment transport model were those average values obtained in the tests with DWP longer than 24 h. A linear relationship [Eq. (8)] was implemented for the evaluation of the M parameter for each applied shear stress (τ_b) during the simulations, valid for values of τ_b higher than 0.40 $\mathrm{N/m^2}$. For lower values of τ_b, the value of M was constant and equal to 0.05

$$M = 0.725 \cdot \tau_b - 0.0487; \qquad \tau_b > 0.40\ \mathrm{N/m^2} \tag{8}$$

Modeling Sediment Transport in the Case Study Catchment

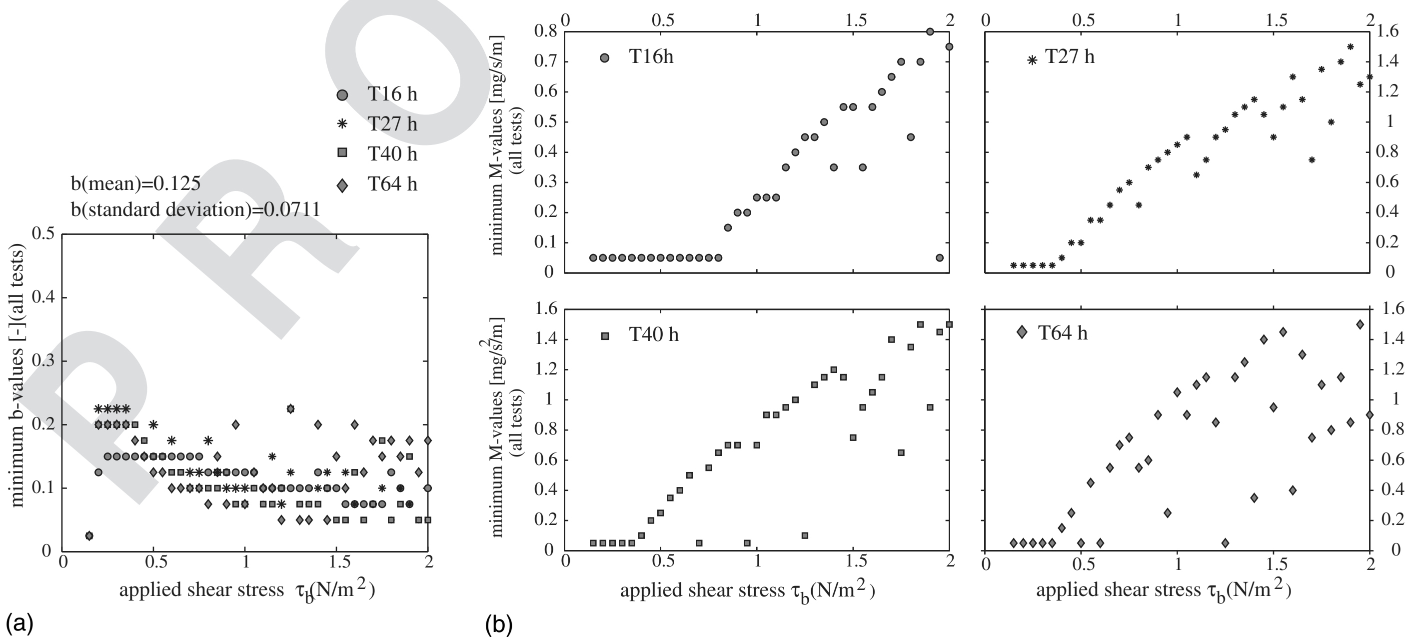
Hydrodynamic predictions were obtained from the calibrated SWMM5 model for the four rainfall events 1 to 4 from Table 2. These predictions were input into the sediment transport model using Skipworth's erosion relationship calibrated with the case study sediment. Initial conditions for the available in-pipe sediment deposits were set to a 5-cm-deep sediment deposit, because this allowed for analysis of sediment transport not to be limited by the availability of sediment in the simulations (i.e., after all the simulations there was still sediment left in each pipe). This ensured that the initial model boundary conditions did not impact on the model predictions. A selection of computation time steps were examined



F8:1 **Fig. 8.** Bed strength profile in depth of the sediment layer

Table 5. Comparison of the Values of Transport Parameters Obtained from Previous Experimental Studies (Rushforth 2001; Skipworth et al. 1999) and the Values Obtained in This Study

	Parameter		Values obtained in this study	Skipworth et al. (1999) 1:500 slope	Skipworth et al. (1999) 1:1,000 slope	Rushforth (2001) (validation of Skipworth model)	
T5:1	Parameter		Values obtained in this study	1:500 slope	1:1,000 slope	Rushforth (2001) (validation of Skipworth model)	T5:2
T5:3	Material used		Sewer sediments	Crushed olivestone		Crushed olivestone	
T5:4	M	(g/s/m^2)	0.5–1.5	2.0	0.35–0.65	0.73	
T5:5	b	(-)	0.125	0.45		0.93	
T5:6	d'	(mm)	32–64	7	3.8	7.2	
T5:7	τ_{cs}	(N/m^2)	0.15	0.20	0.10	0.07	
T5:8	τ_{cu}	(N/m^2)	1.07–1.38	0.50	0.20	0.37	



F9:1 **Fig. 9.** Variation on the parameters b and M values against applied shear stress for all the dry periods tested and were seen to influence the simulated erosion rate. A time step higher than 1 min started to reduce the peak values of sediment concentration; hence, a time step of 20 s was used.

In this study, based on previous research (Ahyerre and Chebbo 2002; Gromaire-Mertz et al. 2001; Tait et al. 2003a), it was hypothesized that the sediment transport inside pipes due to incoming rainfall runoff does not include significant sediment wash-off from catchment surfaces, and that the main source of suspended sediment is reerosion of previously deposited in-pipe sediments.

Sensitivity Analysis

A sensitivity analysis of some parameters of the erosion model was carried out by applying controlled variations of their values in a valid range. In particular, the effect and influence of the bed porosity and the bulk density were estimated. Porosity and bulk density were both included in the model in order to calculate the volume of eroded sediments, which enables an update of the remaining sediment deposit depth available for erosion. Porosity of the sediments was initially assumed as 0.20 based on initial measurements ($p = 0.215 \pm 0.05$ performed by desiccation of fresh samples at 105°C during 24 h). During the sensitivity analysis, the porosity values were changed over the range 0.10 to 0.30, because sewer deposits with fats and greases have been observed to have porosity ranging from 0.10 to 0.24 (Keener et al. 2008). No significant influence on the eroded sediment depth evolution was observed under porosity variation. Results obtained by using the event 2 data are shown as an example in Fig. 10(a). Less than 8% of variation in sediment concentration peak and around 10% in sediment mass mobilized was simulated, compared with simulation results obtained with $p = 0.20$.

The effects of changes in the sediment bulk density in the assessed range of variation for the local sediments (1,066–1,458 kg/m^3; average 1,310 kg/m^3) were also verified [Fig. 10(b)]. For event 2 shown as an example, variation from values calculated with the average sediment bulk density were found between 1.5 and 6.4% regarding maximum sediment concentration, and between 9.4 and 16% regarding total mass of sediment mobilized.

The greatest influence on the sediment transport loads is exerted by the hydraulic conditions. The remobilization of sediments is directly related to the hydraulics that determined the boundary shear stress values.

Model Results and Performance

The performance of the coupled SWMM5 and the calibrated Skipworth model (Fig. 5) was tested by comparing measured versus modeled sediment peak concentrations and calculating NSE [Eq. (5)]. Performance of the sediment transport model was analyzed in the periods for which SS concentration was measured and the obtained values are shown in Table 6.

Unfortunately, the total mass of sediment could not be considered for testing model performance because of the adopted sampling strategy, addressed mainly to collect the first flush by including a sampling collection for a total of 120 min which in most cases covered the first part of the rainfall event duration.

Fig. 11 shows the sediment transport loads evolution assessed by the proposed model which is based on the relationship of Skipworth with calibrated parameters. The SS concentration values obtained were represented as an average value over the pumping interval (pumping-cleaning cycle in sample collection).

During the rain event 1 [Fig. 11(a)], the first phase of runoff arriving to the outlet of the catchment generates an increase in water depth that was lower than the threshold water depth established for the start of the operation of the automatic sampling collection. Thus, the first SS peak that can be observed in the modeling results [Fig. 11(a)] were not covered by the measured SS data. Collected SS concentration data corresponds instead with a second simulated peak when greater flow rates triggered the collection of samples.

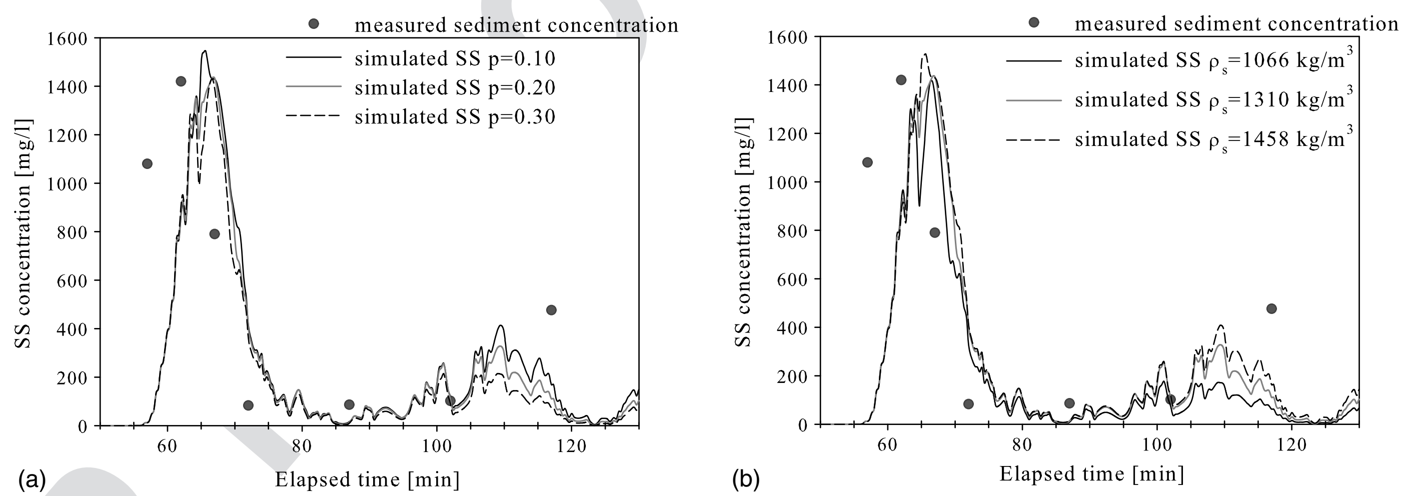


Fig. 10. Influence of the variation of characteristic sediment parameters on the evolution of sediment concentration over time for Event 2: (a) influence of the porosity of sediments; (b) influence of the density of sediments

Table 6. Performance Evaluation between Observed and Simulated Suspended Sediment Transport Evolution

Rain event	Event 1 (September 17, 2010)	Event 2 (May 31, 2011)	Event 3 (October 24, 2011)	Event 4 (July 13, 2011)
Relative error of peak in sediment concentration (%)	14.4	1.1	38.3	89.1
Nash-Sutcliffe efficiency	0.80	0.85	0.73	−0.18

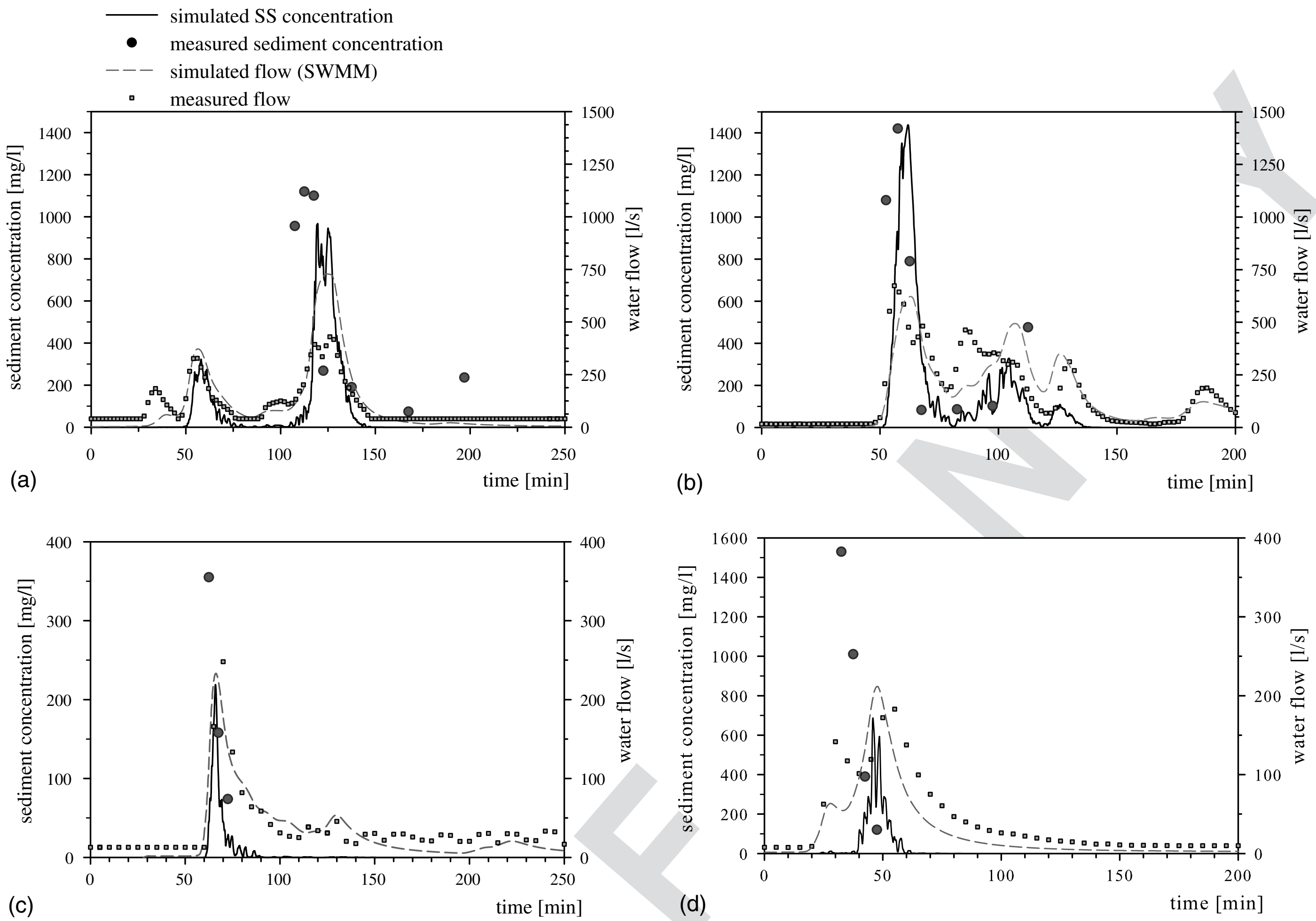


Fig. 11. Sediment transport loads evolution; measured and simulation values based on the proposed model with adapted transport parameters assessed for high organic sediments: (a) Rain Event ID 1; (b) Rain Event ID 2; (c) Rain Event ID 3; (d) Rain Event ID 4

It can be observed that there is a slight delay (6 min) between the sediment concentration peak time measured and simulated during the event. It can be hypothesized that this could be due to the 4-min delay between observed and measured peak flow. The 4-min delay observed at Fig. 11(b) between simulated and measured C_{SS} for the event 2 might also be linked with delays in the hydrodynamic results (8-min delay between observed and measured peak flow from Table 4).

Both the NSE values and visual analysis of the pollutographs (Fig. 10) indicated a good fit between simulated and observed data for events 1 and 2, a reasonable fit for event 3, and a poor fit for event 4. Lower total precipitation and lower rainfall intensity for the event 4 might influence the predicted results because the lower shear stresses generated in the SWMM model are very close to the anticipated surface threshold shear stress of the water sediment interface.

Fig. 12 shows that for the events 1 and 2, the applied bed-shear stress (τ_b) observed at the outlet of the analyzed sewer system reaches values higher than the critical value of the deeper layer (τ_{cu}). Meanwhile, much lower values of applied shear stress are observed for the events 3 and 4. In these events, the shear stress does not even reach the level at which the superficial layer (d') is fully eroded. This indicated that for rainfall events in which the shear stress is low and for thin surface layers in which the shear stress threshold changes quickly, such calibrated models struggle to accurately simulate erosion rates.

Conclusions

Transport Parameters Assessment

Based on the laboratory findings for the highly organic sewer sediments collected in this study, it can be confirmed that the critical shear stress values can be linked to the sediment bed depth, and hence the values of the parameters d', τ_{cs}, τ_{cu}, b, and M depend on the characteristics of the sediment and on the structure of the in-pipe deposit.

From the analysis of the results obtained regarding the performance of the parameters, it can be suggested that the variation of the parameter M might be dependent on other sediment characteristics, such as the median particle size (d_{50}) of the eroded sediments. The range of values adopted by b and M might be also dependent on the density of the sediment eroded.

The sediment erosion and transport model performed well for three out of four rainfall events for which flow and suspended sediment data were collected in the case study catchment. It predicted the peak SS concentrations in these events with a Nash-Sutcliffe efficiency ranging from 0.73 to 0.85. However, it needs to be stressed that the collection of the sewer sediment samples for the laboratory analysis is practically difficult, and assumptions had to be made in the design of the consolidation periods to simulate deposition conditions in the sewer environment in the laboratory. The design of the laboratory consolidation conditions may have an

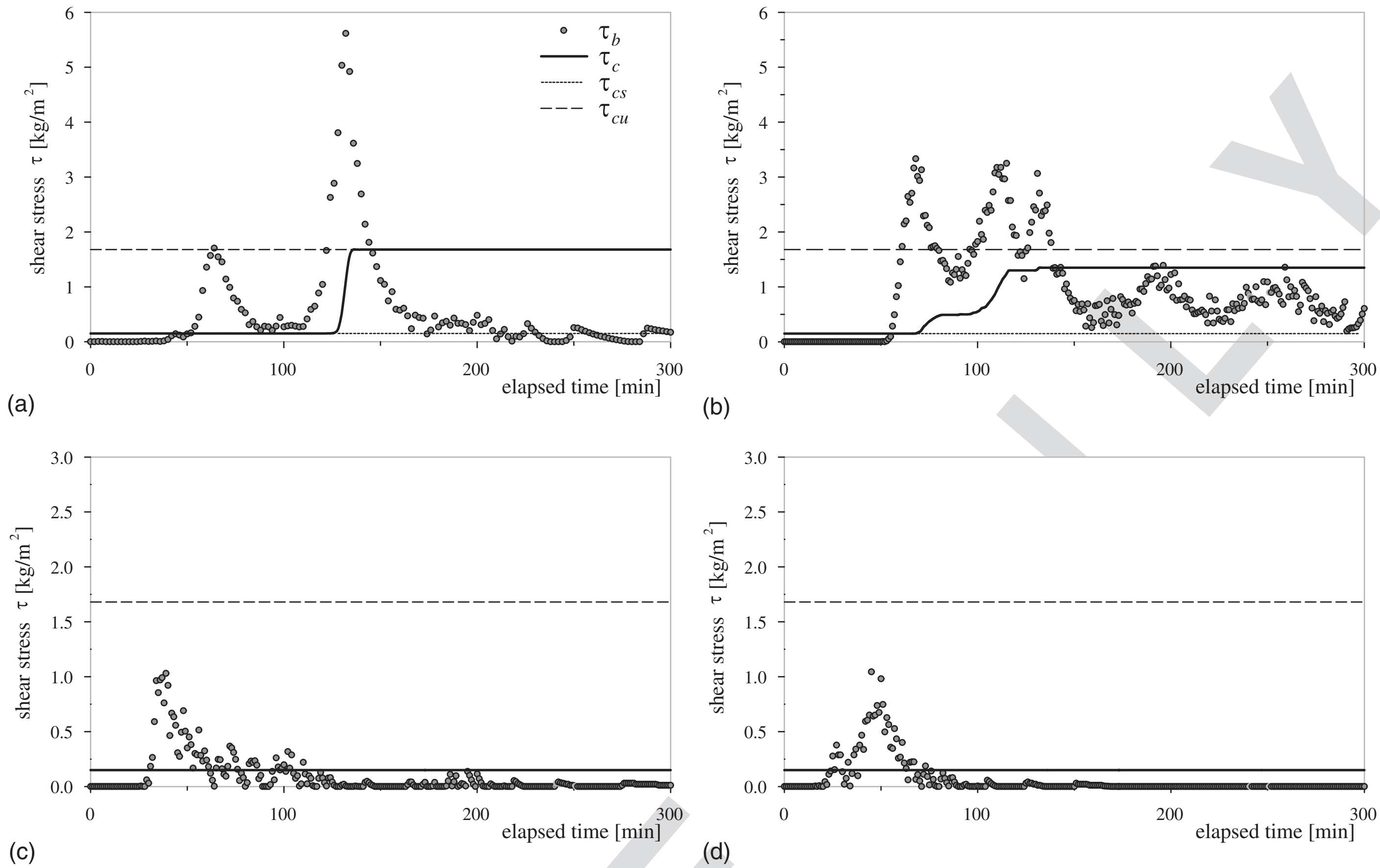


Fig. 12. Applied and critical bed shear stress evolution and sediment bed–depth evolution during erosion process for the different rain events analyzed: (a) Rain Event ID 1; (b) Rain Event ID 2; (c) Rain Event ID 3; (d) Rain Event ID 4

influence on the estimation of the values of the calibration parameters used in the sediment erosion and transport model. Furthermore, temporal and spatial variability of the sediment characteristic in the system might introduce a level of uncertainty that was not examined, because the laboratory tests were all completed using samples collected at a single location on a single day.

Because of site-specific sewer sediment characteristics, the parameters involved in the sediment erosion model must be determined using local sediments. Performing erosion tests in the laboratory gives the possibility of assessing the necessary parameters to deliver a more reliable prediction of in-sewer transport and erosion.

Results from the assessment of the critical shear stress through the erosion tests confirmed the structure of the sediment deposit model proposed by Skipworth regarding the existence of a weak upper layer and increasing resistant erosional strength with depth through the bed. A power law trend was found to describe the variation of the erosional resistance against the depth of the deposit. Furthermore, the values obtained in the present work for the critical shear stress τ_c, varying from 0.15 up to 1.4 N/m^2 (depending on the consolidation period for a deposit of 30-mm depth), are in the range found from previous in situ and laboratory work with real sewer sediments carried out by Mclhatton et al. (2005) and Oms et al. (2008) who reported values in the range 0.15–0.85 N/m^2.

The results from erosion tests also suggested that the behavior of newly deposited surficial sediments subject to dynamic consolidation for up to around 24 h show an increasing resistance against erosion; when the period of consolidation exceeds the 24 h, any further increase in resistance becomes insignificant (Fig. 8).

Further research is needed to identify a more direct relationship between the parameter b and M with the sediment characteristics.

Sediment Transport Modeling Application 650

For the case study described in this paper, it was verified that the initial conditions regarding sediment deposit properties and hydraulic parameters are indeed relevant in the prediction of SS loads released and mobilized from in-sewer pipes during rainfall events. The large variation in the nature and behavior of the deposited sediments, the highly variable hydraulic conditions, and the complexities of the processes occurring in-sewer makes a calibration process and validation against locally measured data essential.

The predictive capacity of the sediment transport model proposed by Skipworth et al. (1999) was verified with NSE between 0.85 and 0.73 for three out of four events. The indicated performance on the results is directly related to an adequate assessment of the values of the transport parameters considering the local sediment characteristics, and to an adequate calibration of the hydraulic model using locally measured rainfall and flow data.

Following the analysis of the simulation results, it can be observed that the rapid change in SS concentrations is due to the quick response of the system influenced by a high level of imperviousness in the catchment as well as the pattern of rainfall. It was concluded that reducing the sampling frequency at the beginning of the event is desirable so as to be able to capture, with more detail, the highly variable start of the pollutograph. Sampling interval adjustments will depend on the catchment characteristics and concentration time on the case study. As an alternative, the on-line probes that can make indirect measurements of the SS concentration could be used to obtain data with a higher temporal resolution. The locally calibrated data can then be directly compared with the temporal pattern of the SS concentration prediction.

Improved first flush prediction is required to better manage the pollution events on receiving natural watercourse pollution through CSOs. The sediment modeling provided a better fit for the three largest rainfall events, indicating that more research may be needed in defining how exactly the weak layer at the very top of the in-sewer deposits erodes.

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Notation

The following symbols are used in this paper:

A_s = sediment surface exposed to erosion (m^2);
b = calibrated transport parameter (-);
C_{SS} = suspended solids concentration (g/L);
d = cumulative depth of erosion (mm);
d_e = sediment eroded depth per time step (mm);
d' = thickness of the upper sediment layer of the deposit (mm);
d'' = thickness of the surficial layer eroded during consolidation period (mm);
d_{50} = characteristic particle size (mm);
E = erosion rate (kg/m/s);
M = calibrated transport parameters ($g/s/m^2$);
V_s = sediment volume (m^3);
ρ_m = sediment-water mixture density (kg/m^3);
ρ_s = sediment bulk density (kg/m^3);
τ_b = applied bed-shear stress (N/m^2);
τ_c = critical shear stress (N/m^2);
τ_{cs} = critical surficial shear stress (N/m^2); and
τ_{cu} = critical shear stress of the underlying layer (N/m^2).

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